Evaluation of soluble phosphorus loading from manure-applied fields under various spreading strategies

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ABSTRACT: A simple model was developed and applied to a dairy farm in the New York City (NYC) water supply watershed to evaluate the effectiveness of various manure spreading strategies for reducing non-point source, soluble phosphorus (SP) pollution. Phosphorus from manure-spread fields is recognized as one of the important non-point source pollutants in the region and there is acute interest in developing economically viable water quality management practices. The NYC watershed initiative, i.e. the Watershed Agriculture Program (WAP), mandated that water quality management practices would be scientifically justifiable based on the best information available (Walter and Walter, 1999). Thus, this project was carried-out to evaluate manure-handling strategies based on the currently available information. The model for predicting SP loading to perennial streams via surface runoff was developed by combining a mechanistic hydrological model with an empirical relationship for SP concentration in runoff. This study showed that, in the short term, because of soil P accumulation associated with a history of dairy farming, the maximum possible reduction in SP loading to perennial streams is about 50%. Exporting all manure from the NYC watersheds attains this. Utilizing the concept of hydrologically sensitive areas (Walter et al. 2000), this study suggests possible SP loading reductions of 25% with all manure remaining on-farm. This study supports and emphasizes the finding by Walter et al. (2000) that the timing and location of manure spreading strongly influences SP transport.

Keywords: Agricultural non-point source pollution, Catskill Mountains, hydrological modeling, hydrologically sensitive areas (HSA), manure management, phosphorus, water quality

The role of phosphorus (P) in eutrophication is well documented (Vollenweider, 1971; Schindler, 1974; Porter, K.S., 1975; Sharpley and Smith, 1992; Correll, 1998). In many non-marine, aquatic systems, algal growth is limited by the concentration of biologically available P (Tiessen, 1995). Sharpley and Smith (1992) estimated that dissolved soluble phosphorus (SP) constitutes 69-87% of the P biologically available to algae. Manure-spread agricultural land, primarily dairy farms, is identified as an important source of SP loading to perennial streams throughout the Northeastern United States (Sharpley et al., 1994) and in the New York City (NYC) watersheds, particularly where there are high spatial densities of dairy farms and high animal densities per manure-applied area (EPA, 1990, National Research Council, 1999)

New York City, under the 1997 NYC Watershed Memorandum of Agreement (MOA), must comply with water quality standards for contaminants in drinking water and must maintain a watershed protection program (National Research Council, 1999). The development of strategies for reducing phosphorus loading is an important goal in meeting the MAO. Current approaches for controlling phosphorus contamination, typically traditional soil and water conservation practices, have not proven very effective in controlling dissolved pollutants like SP (Walter et al., 1978). A more promising dual strategy for decreasing long term P loss to streams consists of reducing P content of animal feeds (Klausner et al., 1998) and applying manure to land that is least susceptible to runoff (Gburek and Sharpley, 1998; Walter et al. 2000). To modify manure-application procedures, a method to estimate the pollutant-delivery to streams is required. If based on our best understanding of hydrology and pollutant movement, including this method in "nutrient management plans" or "Whole Farm Plans" could significantly improve stream quality. This study follows in the vein of Water et al, (2000) who suggested the possibility of significant reductions in agricultural non-point source pollution if contaminate loading avoids hydrologically sensitive areas (HSA's).

This paper develops a simple model for estimating SP loading to Catskill streams and lakes and applies it to a farm in New York State's Catskill Mountains to evaluate the effectiveness of different manure-spreading strategies. This study is not exhaustive with respect to spreading strategies but rather examines a few extreme examples and a number of schemes based on HSA theory relative to the region's historical practices. The purposes of this paper are to advance an approach for evaluating the effectiveness of management practices and suggest some unique manure-spreading strategies, not to present closure on the development of manure handling practices.

Methods and Materials

"Edge-of-field" SP losses are predicted using a distributed hydrological model to determine variable source area runoff and an empirical relationship for SP concentration in runoff. This empirical SP relationship is a function of manure application density, time since manure application, and soil test phosphorus.

The hydrology is simulated as distributed, variable source area hydrological processes on a watershed basis using the Soil Moisture Routing model (SMR) (Zollweg et al. 1996, Frankenberger et al., 1999; Kuo et al. 1999). SMR was developed especially for shallow soils overlying a relatively restrictive layer such as the fragipan commonly found in the Catskills. The model was coded in shell script commands within the Geographic Resources Analysis Support System (GRASS) (CERL, 1993; Mitasova et al., 1995). The simulations were performed using a daily time step.

Figure 1 illustrates the functionality of SMR. Water balance equations in SMR operate on rasters or grid cells distributed throughout a watershed. For each cell the soil is divided into two layers, potential root zone and subsoil. The potential root zone is divided into the actual root zone (from which evapotranspiration occurs) and the remaining part into which the roots can penetrate during the growing season. The change of soil water in a cell layer is calculated by summing the water fluxes into and out-of a layer. The flux mechanisms include the daily precipitation, evapotranspiration, vertical water flux between soil layers, and lateral subsurface flows, a.k.a. interflows. The lateral flow depends on the local hydraulic con-

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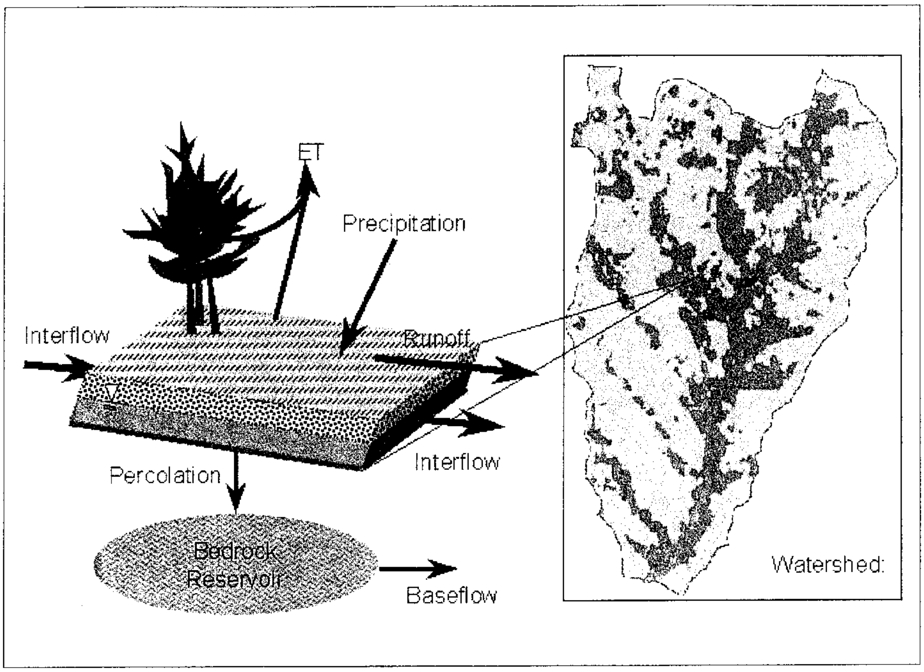

Figure 1. Schematic of the SMR model's water balance.

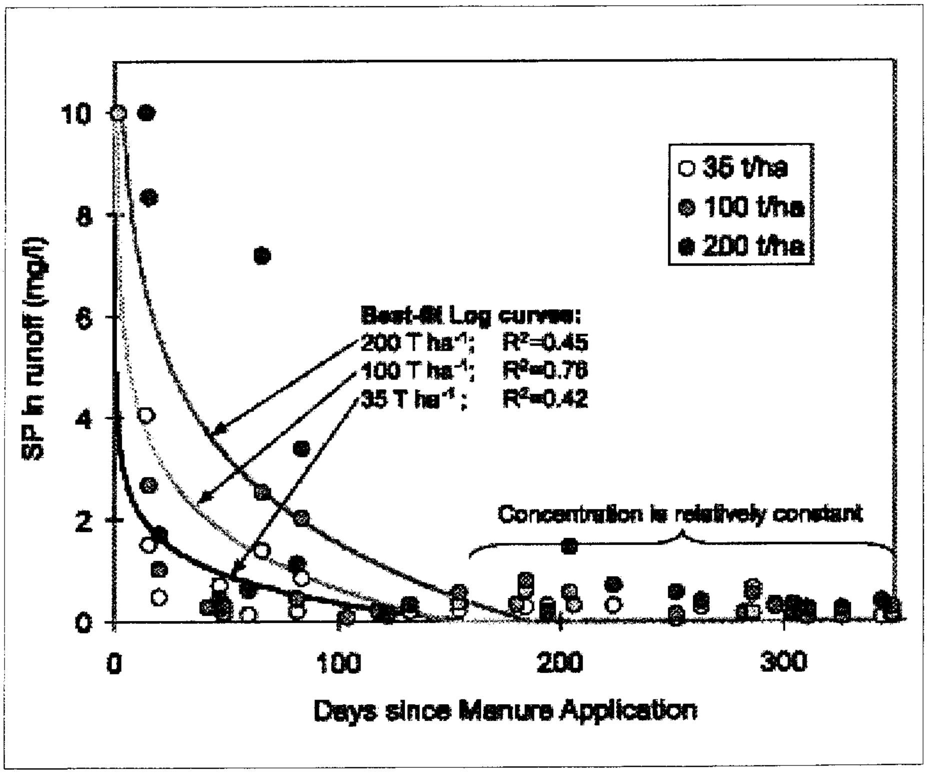

Figure 2. Dissolved phosphorus concentration in runoff vs. days since application for three application densities. Symbols are data: red=200 T ha^{-1} (220 Ton ac^{-1}), blue = 100 T ha^{-1} (110 Ton ac^{-1}), open = 35 T ha^{-1} (39 Ton ac^{-1}). Lines are best-fit logarithmic curves.

ductivity, a function of moisture content, and local land slope, i.e. a kinematic approximation for hydraulic gradient. Local runoff occurs when the soil reaches saturation or precipitation intensity is greater than local saturated hydraulic conductivity. Evapotranspiration is based on the Thornthwaite-Mather procedure (Steenhuis and van der Molen, 1986). During the winter, snow accumulation and snowmelt are included. Because it is a distributed model, runoff generated from individual fields or even portions of fields can be easily ascertained.

The SP concentration in the runoff, C_{dp}, was calculated by adding the SP contributions of the manure, C_m, to the background concentration of SP, C_b from the field soil

$$C_{dp} = C_m + C_b \tag{1}$$

The SP concentration in runoff originating from the manure was obtained by regressing the data from the Catskills collected by Scott (1998); Scott's (1998) data were supplemented with Klausner et al.'s (1976) data collected at the Cornell University Aurora Farm to obtain more points and add robustness to the empirical relationship. Trends in runoff SP concentration as a function of time since application were determined for manure applications of 35 T ha^{-1} (39 Ton ac^{-1}), 100 T ha^{-1} (110 Ton ac^{-1}), and 200 T ha^{-1} (220 Ton ac^{-1}) (Figure 2). A surface was fit through the three regression curves (Figure 2) to obtain a single empirical equation for C_m as a function of manure application density and time since manure application.

$$C_m = M^{0.66}\,(0.373 - 0.078\ln(t))\quad 10 \ge C_m \ge 0 \tag{2}$$

where C_m is the SP concentration in the runoff (mg L^{-1}), M is manure application density (T ha^{-1}), and t is time (days). This function is shown in Figure 3.

The maximum dissolve phosphorus concentration was set at 10 mg L^{-1} (ppm) based on regional barnyard runoff concentrations (Robillard et al., 1983). Using Equation 2, the SP concentration from manure as a function of time after spreading is shown in Figure 3.

To simulate multiple manure applications to the same field, C_m is calculated with Equation 2 for each daily manure spreading and a cumulative C_m is determined by summation with the condition that it cannot exceed 10 mg L^{-1} (ppm).

The background concentration, C_b (mg L^{-1}), was determined based on Morgan extractable P (10% sodium acetate in 3% acetic acid buffered to pH 4.8, using a 1:5 w/v soil:solution ratio; Morgan, 1941). The Morgan P in soils typical of the study watershed, specifically moderately well drained Willowemoc channery silt loam or coarse, loamy, mixed, frigid Typic Fragiochrept, the desorption-partition coefficient, k_d, was 144 L kg^{-1} Scott (1998). Thus the equilibrium dissolved phosphorus concentration is:

$$C_b = \frac{P_m}{2k_d} \tag{3}$$

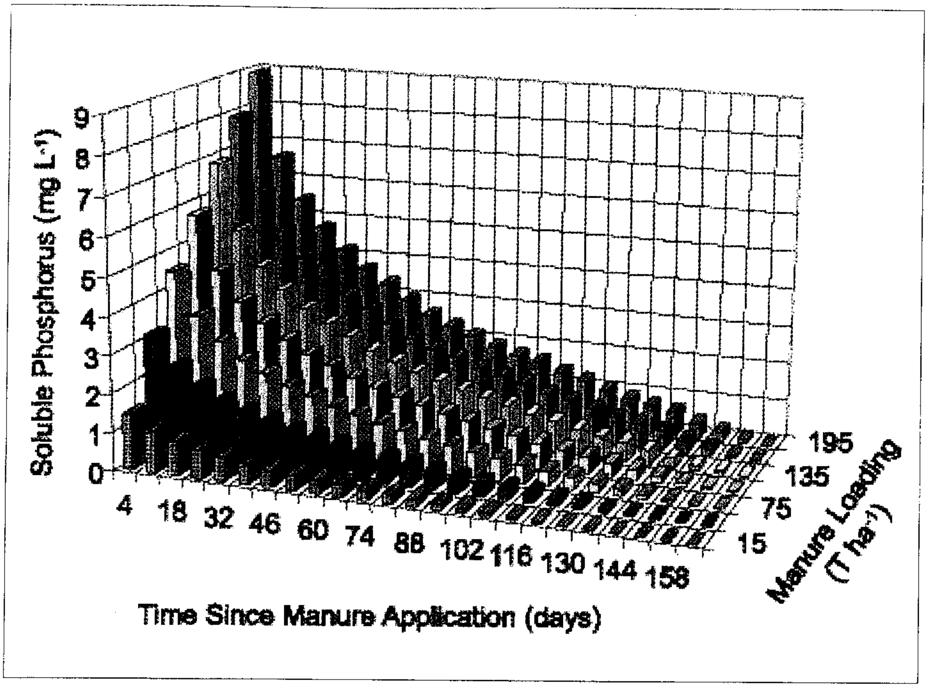

Figure 3. The model SP concentration in surface runoff as a function of manure loading rate and time since manure application.

where P_m is the Morgan extractable P in mg kg^{-1}. The phosphorus test results are usually given in lb $acre^{-1}$ in the top 15-20 cm (5.9-7.9 in) of the soil. Unit conversions show then that by dividing the amount the Morgan extractable P (lb $acre^{-1}$) by two, the Morgan P is obtained in mg kg^{-1}. Though recent research shows that only the top 2-3 mm (0.08-0.12 in) of the soil interacts chemically with runoff, (Zhang et al., 1997), in shallow-soils systems chemicals may have the potential to be transported upwards through the matrix during saturation. This makes the 15-20 cm (5.9-7.9 in) depth used in typical soil phosphorus tests potentially applicable to this model. Regardless, these data are typically available and/or easily attainable, making the model appropriate to management situations.

Table 1: Summary of Manure Spreading Strategies.

Strategy	Storage	Description
Current	No	Follows current rubric for manure application decisions
No Manure	—	All manure exported from the watershed
April Application	Yes	All manure applied evenly over all fields in April
October Application	Yes	All manure applied evenly over all fields in October
Crop Based	Yes	Manure applied based on crop nitrogen demands during periods of the year correlating with normal cropping activities
HSA30	No	Manure is applied daily but never to a field classified as hydrologically sensitive (>30% prob. of runoff)
HSA15	Yes	Manure is applied periodically and never to a field classified as hydrologically sensitive (>15% prob. of runoff)
Modified HSA15	Yes	Same as "HSA15" but October spreading is restricted to corn fields with all other field receiving manure earlier in September.

The total SP load (mass) from the entire farm is the sum of the load transported from each field obtained by multiplying each field's SP concentration by the predicted runoff for each field.

In the following sections we will compare eight different manure management practices.

Field Application and Manure Scheduling Strategies. Field application of the model incorporated real and hypothetical manure spreading schedules. Development of hypothetical strategies focused on the hydrologically sensitive area (HSA) concept (Walter et al. 2000). HSA's are localized areas in the landscape that are prone to saturate during a storm and produce runoff. The extent of the saturated areas depends on the initial soil moisture content, the local topography, and the amount of rainfall. The spatial extent of HSA's varies seasonally as well as during a storm, therefore, some areas that are hydrologically sensitive for one part of the year may be insensitive during another.

The manure scheduling study focused on a farm located in New York's Catskill Mountains in one of the NYC watersheds. This farm had very good records of farm activities and, according to County Conservationists, had good environmental practices. The farm consisted of 40 fields (143 ha (553 ac)), 110 milking cows, and generated, on average, two loads of manure per day (730 loads $year^{-1}$). The manure spreader used on the farm held 3 tons of manure. When spread on the field at a rate of 0.2 ha per load, the manure loading density for one load of spread manure was, on average (15 T ha^{-1} (17 Ton $acre^{-1}$)). For this analysis, predicted dissolved phosphorus exports among eight different manure-spreading scenarios were compared for 5 years of simulation using the weather records for 1991-1995.

Because the model does not biogeochemically balance P, it is inappropriate to use this model to predict long-term trends is SP loading. Rather, the appropriate use of the methodology presented here is to estimate short-term effects. Five years were simulated for each strategy to consider annual meteorological variability. The manure spreading scenarios investigated in this study generally attempt to meaningfully interface with farm activities such as planting and harvesting. For example, the strategies avoid spreading manure on planted cornfields. Descriptions of the eight spreading strategies are presented below. Table 1 provides a succinct summary of the eight strategies.

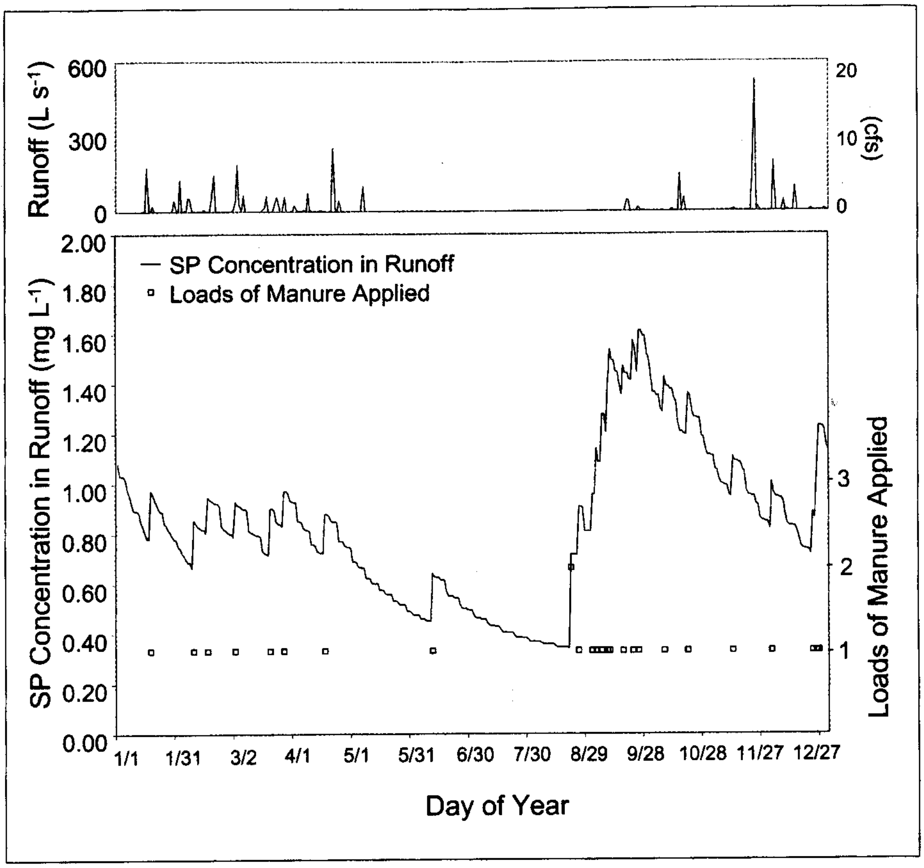

Figure 4. Example of predicted SP concentration in surface runoff from a field in the Catskills (1991) under the *Current* strategy. Note: 1 load of manure is 3 T (3.3 Ton).

Descriptions of manure spreading strategies:

(1) Current: This spreading schedule represents the historical and current manure-spreading schedule. Factors influencing manure-spreading decisions were identified from interviews with local farmers. Manure spreading is mainly a function of the crop, time of year, distance from the barn, and the steepness of the access road between the barn and the field. Two loads of manure are spread daily. Manure is not spread on newly seeded alfalfa or cornfields during the growing season. Alfalfa fields may receive manure during two weeks of the growing season immediately after the first cutting and again between cuttings. All fields can only receive one manure load per day with exception of a small subset of fields that, because of their particularly convenient proximity to the barns, may receive up to two loads per day. A random number generator determined the specific fields receiving manure on a given day within the rubric described. Consistent with the majority of farms in the region, this strategy requires no storage. (Table 1)

(2) No Manure: This strategy represents the extreme lower limit of possible SP export from the farm. In this schedule all manure is exported from the watershed. Therefore, the total SP transported for the year is only a function of the phosphorus content in the soil. (Table 1)

(3) April Application: This is an idealized schedule in which all 730 loads of manure are spread in April; twenty-five loads are spread per day for the first 29 days. The driest fields received manure at the beginning of April and the wettest fields received manure at the end of April. To determine ranking of fields from driest to wettest, a 30 year (1960-1990) hydrological simulation was run on the farm using the SMR model and a frequency analysis was performed on the simulated April 1 soil moisture contents for each field. This strategy assumes a one-year manure storage capacity. (Table 1)

(4) October Application: Like *April Application* (3), this is an idealized schedule in which all 730 loads of manure are spread in October in a manner similar to that described in the *April Application*, schedule (3); The main difference is that the wetter fields receive manure before the drier. (Table 1)

(5) Crop Based: Like the *April* and *October Application* scenarios (3 & 4), this schedule assumes the farm has a year's worth of manure storage capacity. Timing of spreading loosely accommodates crop nutrient demands. For example, in the spring manure preference is given to corn over hay. In this region there is generally much more manure than needed to meet crop nutrient requirements. Out of the 730 total loads of manure accumulated during the year, 191 are applied to corn fields during April, 181 loads are applied to alfalfa fields in the first half of July, and the balance is applied to all fields between September 26 and November 4. Each field receives at least enough loads to totally cover the field once. The farmer spreads on the same field until the field receives all its required loads for the month before moving to the next field. It is assumed that the farmer plants corn on April 25th. The first cutting of alfalfa is assumed to be over by July 1st, and therefore all alfalfa fields are covered once with manure between July 1st and July 15th. (Table 1)

(6) HSA$_{30}$: This scenario uses the HSA concept by restricting manure application from areas prone to generating runoff. The approach combines crop nutrient needs with a method presented by Walter et al. (2000), which attempts to balance the need for manure disposal with water quality. Walter et al. (2000) suggested that fields with greater than 30% daily probability of generating runoff in a month are classified as HSA's and therefore not suitable for manure application during that month. Using 30 years of SMR simulations (1960-1990) on the farm, monthly probability of runoff generation was determined for each field. Fields were ranked monthly from smallest to largest probability of runoff. Fields are allocated to receive manure by applying manure to the consistently least hydrologically sensitive fields during the wettest months. All fields received the same amount of manure as received in the *Crop Based* schedule (5). This strategy requires no manure storage. (Table 1)

(7) HSA$_{15}$: This schedule assigns fields HSA status (i.e. unsuitable for manure spreading) if they had more than a 15% chance of generating runoff. From a management perspective this is a more-restrictive classification than *HSA$_{30}$*. Because of ubiquitous hydrological sensitivity during the very wet winter months, manure application occurs only in April, July, September, and October and thus manure storage is required. During the second half of April all non-HSA fields are covered at least once with manure (86 loads). During the first two weeks of July, between cuttings,. all alfalfa fields are

covered at least once (182 loads). In September, after harvesting, all the alfalfa fields are covered again with manure (182 loads). In the first half of October manure is spread on all fields that are not HSA for October through December (280 loads). (Table 1)

(8) Modified HSA_{15}: This schedule is nearly identical to schedule 7 except in this schedule October spreading is limited to cornfields. The manure that the grass and alfalfa fields received in the first half of October in schedule 7 is spread during September. This modification allows more time for SP on these fields to become unavailable for runoff transport before the hydrologically active winter months. (Table 1)

Results and Discussion

Figure 4 shows an example of the predicted SP concentration in runoff from a field on a farm in the Catskills that experienced daily manure spreading in 1991 under *Current* strategy. Peaks in the time series represent days when manure was spread on the field. As seen in Figure 4, this field received the most manure during the fall. Figure 5 shows the cumulative SP export from this field. The simulated trends of relatively high SP export rates in the spring and fall and very low rates during the summer match trends in measured data from small-scale research sites in the Catskills (Scott, 1998).

Figure 6 shows the average annual SP exported from the farm during 1991 through 1995 under the various manure spreading strategies. Clearly exporting all the manure off the farm resulted in the least SP export. Interestingly, the *No Manure* scenario only reduced the SP export by 50%, presumably because of large sources of P in the soil that have accumulated over many years of manure spreading. Note that the approach outlined in this study does not address changes in this source of P. Obviously, the *No Manure* strategy represents the maximum potential SP reduction. The dashed lines in figure 6 show the current SP export level and the average minimum level as determined by the *No Manure* scenario. Without exporting manure from the watershed, only the manure spreading strategies that accounted for HSAs reduced SP loading below the current level. The *Modified HSA_{15}* strategy reduced SP loading to approximately half the maximum potential reduction or to about 75% of the current the spreading schedule.

Figure 7 shows the yearly exports under each strategy. For comparison, the solid lines in Figure 7 are the average levels shown in Figure 6. Except for 1995, the *Modified HSA_{15}* schedule had the lowest total yearly SP export of all the strategies except for, of course, the *No Manure* scenario. During 1995, the schedules that applied the majority of the manure in the spring typically had lower SP exports than

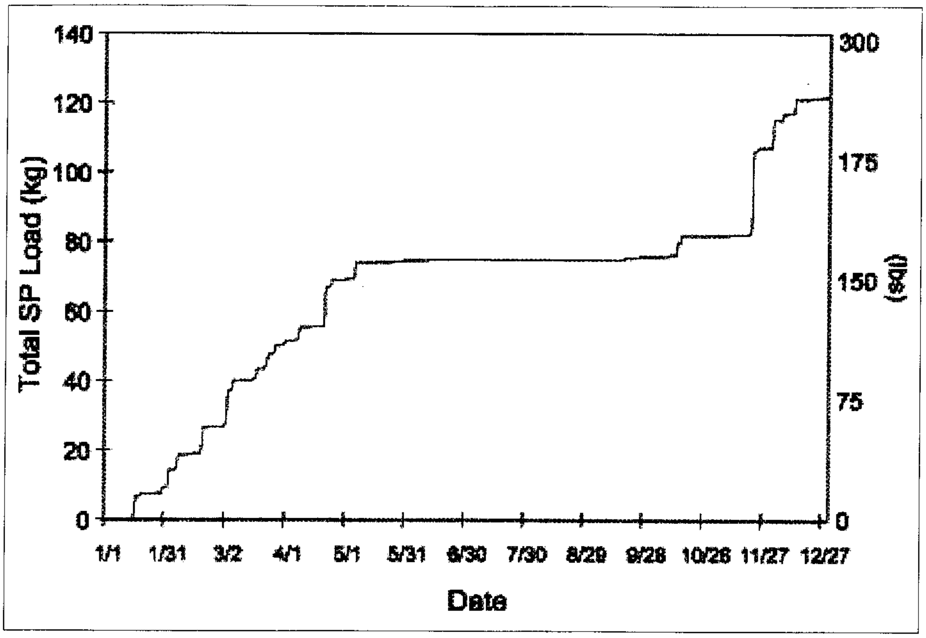

Figure 5. Example of predicted cumulative dissolved P export in surface runoff from a field in the Catskills (1991) under the *Current* strategy.

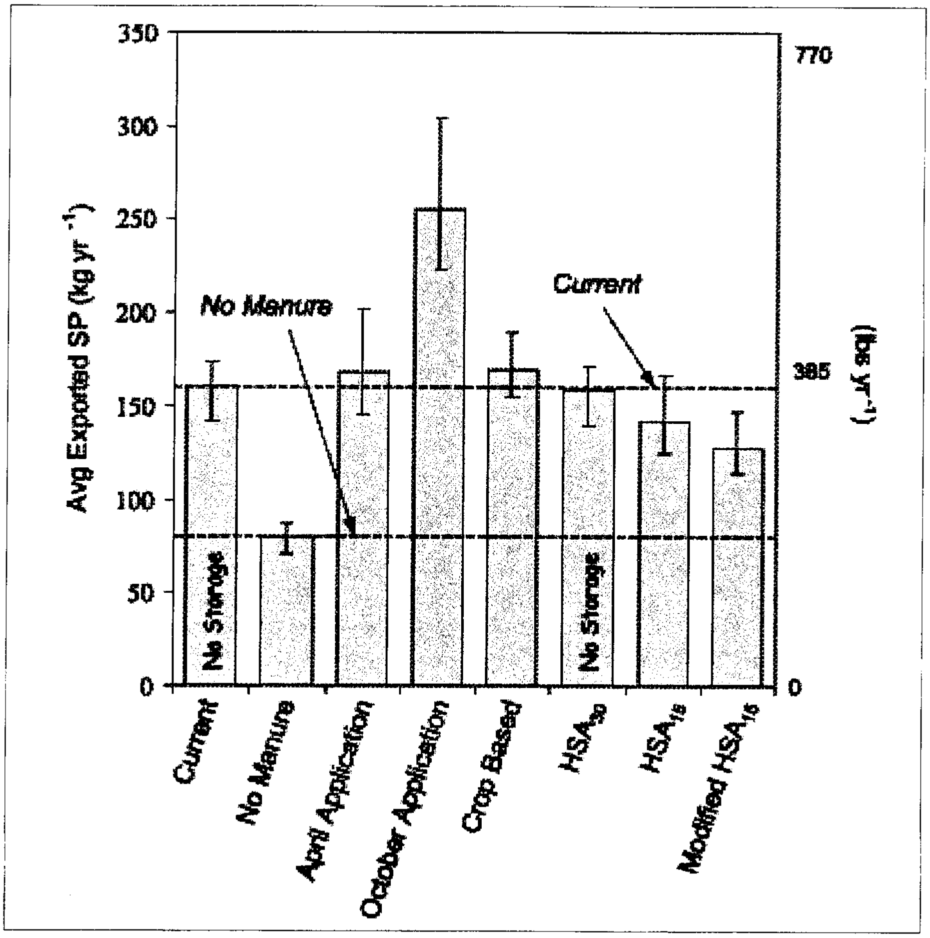

Figure 6. Predicted yearly averaged dissolved phosphorus exported from the farm during 1991 through 1995 (+/- 1 standard deviation error bars).

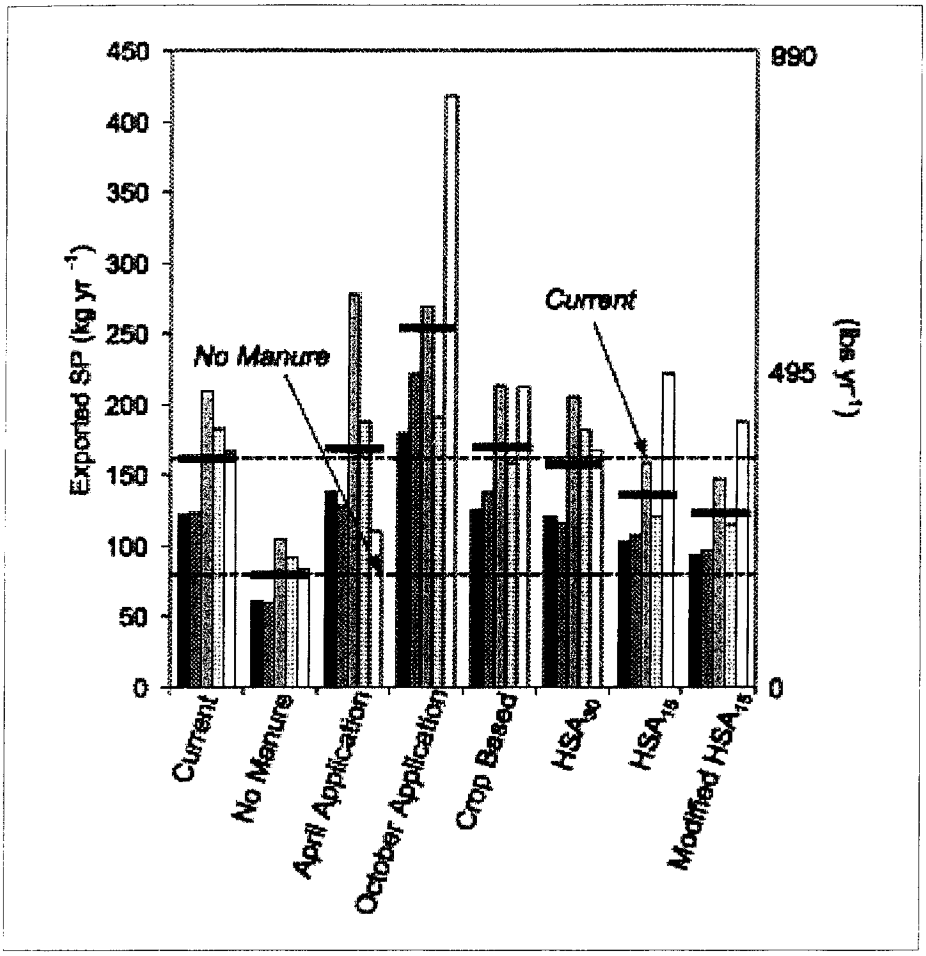

Figure 7. Annual dissolved phosphorus exported from the farm during 1991 (darkest bars) through 1995 (lightest bars). Short solid lines are averages. Dashed lines indicate the average SP exported under the *Current* (upper line) and *No Manure* (lower line) strategies.

the *Modified* HSA_{15}; this is especially apparent for the *April Application*. The SMR predicted annual runoffs from the fields for 1991 to 1995 were 376, 381, 640, 561, and 513 thousand cubic meters (13200, 13500, 22600, 19800, 18100 ft^3) respectively. As can be seen from Figure 6, the annual SP exports for the various scenarios don't generally correlate strongly with these annual runoff values or with each other. *This suggests that the timing and location of manure spreading strongly influences SP transport.*

The reason the *Modified* HSA_{15} strategy produced less SP than the HSA_{15} approach is that a large amount of manure was applied in September rather than October. Because late fall and early winter are high runoff periods, moving as much manure spreading as possible away from these seasons ensured that the associated concentrations were low by the time the watersheds became hydrologically active; i.e. the SP concentration in the runoff during the high runoff winter months was much less for the manure spread in September than October.

Walter et al. (2000) derived the HSA_{30} strategy based on a foundation of balancing water quality needs with farm management requirements, i.e. this strategy tried to minimize land use restrictions and still address water quality. This study suggests that the HSA_{30} strategy may only be a slight improvement on current practices and, as Walter et al. (2000) suggested, it is probable that HSA criteria will have to be more stringent than areas exceeding 30% probability of runoff generation. This study is not conclusive on this point because the farm used is currently relatively environmentally conscientious with regards to its management practices. More significant improvements may be found by applying HSA_{30} to farms that place less importance on water quality. Also note that, other than the *Current* strategy, this was the only scenario that required no manure storage.

These results suggest that developing farm management strategies that account for hydrological sensitivity may reduce water quality risks in the Catskills. Improved understanding of the potential availability of SP for runoff transport will help modify management practices that use HSA-based concepts to improve water quality.

Summary and Conclusion

This study supports and emphasizes the finding by Walter et al. (2000) that the timing and location of manure spreading strongly influences SP transport.

This method for predicting dissolved phosphorus delivery from manure applied fields to perennial surface water bodies can be used as a tool to evaluate the relative improvement in water quality due to implemented manure management practices on a given farm. The model results in this study support the concept that considering hydrological sensitivity can reduce water quality risks. Namely, avoiding the application of potential pollutants to HSA's is a viable approach to reducing surface water contamination due to polluted runoff. This study provides a methodology for further development of better hydrologically based management practices. It is important to reiterate that the model described here has a strong empirical component that makes its utility relatively geographically limited; the overall approach, however, should be widely applicable.

One issue not addressed by this study is the long-term changes in the soil P reservoir. Given that the current high levels of P in the soil are largely attributed to historical manure spreading, it's conceivable that this source will change over time and is significantly impacted by farm practices. The temporal scales for these changes are unclear, though research suggests that they are on the order of decades for this region (Scott et al., 1998). The model described herein is capable of employing this information as it becomes available.

The method used in this study can be most significantly improved by addressing the empirical relationship for runoff SP concentration. For example, additional relationships might include vegetative cover and field practices. Also, currently the empirical SP relationship does not vary with seasonal factors like snowmelt. Unfortunately, due to data limitation, the model has not been corroborated against field observations so judging improvements in the model due to any changes will be difficult to assess. Due to these limitations this method is best suited for predicting relative rather than absolute quantities of SP delivery. A mechanistic component for SP would be most desirable but it has to maintain appropriate parameterization needs to be usable in a management situation.

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Modeling the effects of complex topography and patterns of tillage on soil translocation by tillage with mouldboard plough

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ABSTRACT: The design and results of a tillage field experiment conducted in Central Spain in 1995/96 are presented. Soil translocation models of the type d = f(ST;SP), in which the absolute, forward and lateral translocation are calculated as functions of the slope gradients simultaneously in both directions parallel (ST) and perpendicular to the direction of tillage (SP), were developed. It was determined that: a) forward translocation d_{DT} *simultaneously is inversely correlated with the slope ST and directly correlated with the slope SP; b) lateral translocation* d_{DP} *is inversely correlated with the slope SP; and c) the distance in the actual direction of soil movement* d_D *only is inversely correlated with the slope ST. From simulation results it was concluded that the effects of complex topography and of the interactions between topography and patterns of tillage on soil translocation, are much more important than predicted using one-dimensional or diffusion type models of soil translocation.*

Keywords: Modeling, mouldboard plough, soil degradation, tillage erosion, tillage translocation

Soil translocation and redistribution in agricultural fields due to the direct action of tillage has been identified as a soil degradation process by erosion (tillage erosion) and as an important geomorphic process in agricultural landscapes (e.g. Mech and Free, 1942; Papendick and Miller, 1977; Lindstrom *et al.* 1992; Quine *et al.* 1993). The first experimental field work on the soil redistribution by tillage dates back to the 1940's (Mech and Free, 1942), but the importance of the process was not acknowledged by the scientific community until the 1990's. Based on the experimental studies of Lindstrom *et al.* (1990, 1992), the high intensity of the process was detected and it was recognised that this process may be main mechanism of soil degradation on cultivated fields. Afterwards several field experiments have been carried out to quantify the displacement of soil by different tillage implements.

Special attention should be given to the tillage practices with a mouldboard plough. The mouldboard moves the whole soil layer with a more or less uniform depth of generally between 24 cm (9.5 in) and 40 cm (15.7 in). This superficial soil layer becomes inverted and displaced following a oblique angle to the path of the tractor (d_D in Figure 1), i.e. forward in the direction of tillage (d_{DT} in Figure 1) and laterally in a perpendicular direction to that of tillage (d_{DP} in Figure 1).

Specifically in the case of the mouldboard plough, the works of Lindstrom *et al.* (1990 and 1992), Revel *et al.* (1993), Govers *et al.* (1994), Lobb *et al.* (1995) stand out as does the recent study per-

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